Round 39. PageNet responds to this jump with an even stronger jump to $35 million, signaling that PageNet will not be content with only the two 50/50s. Dubis apparently has dropped out. The battle for the two 50s is limited to PageNet, PageMart, and American Paging.

Round 40. American Paging makes a much weaker jump on license 10 to $32.5 million. American Paging appears to be the weakest of three firms still bidding. Amid protest from the bidders, the FCC announced that round 40 would be the last of the evening. The bidders saw the end in sight and wanted to finish tonight.

Friday, July 29. The bidding began at 9 AM. The FCC announced, "From round 41 forward, we are using 15 minute rounds and the withdrawal period will be 2 minutes long." This duration was so short that it became impossible for bidders to work from their "war rooms." Bidding teams moved down to the bidding room for the remainder of the auction. So long as the bidding activity remained only on the 50s, there was little strategizing to occur so the short time between rounds did not pose a problem to the bidders. Indeed, it was the bidders that asked for the shorter rounds. The FCC was aware that if bidding reopened on the 50/50s or 50/12.5s, then the rounds would need to be extended.

Round 41. PageMart responds with a jump to $34.5 million, inviting a challenge from American Paging.

Round 42. American Paging tops PageMart with a bid of $35.7 million on license 10.

Round 43. PageMart responds with a raise to $36.5 million.

Round 44. American Paging shifts its bid of $35.7 million to license 11, challenging PageNet.

Round 45. PageNet responds with a bid of $37 million, besting PageMart's bid of $36.5 million on license 10. PageNet is hoping this will leave PageMart to deliver the knockout punch to American Paging.

Round 46. PageNet's hopes are fulfilled. PageMart bids $38 million on license 11. American Paging is unwilling to top either bid. The bidding ends.

5. Questions for Auction Theory

Auction theory was of enormous value in designing the simultaneous multiple-round auction. The FCC docket on "Implementation of Section 309(j) of the Communications Act—Competitive Bidding" is filled with hundreds of pages of comments and testimony from auction theorists. The debate among auction experts influenced every aspect

of this first spectrum auction. Theory was used in a most practical way—to design a new auction form for an environment that was ill-suited to standard auction forms. Although the experiment was successful, there are several areas where the theorists were pushing beyond the existing theory in recommending the simultaneous multiple-round auction. Also, from a bidder's perspective, existing auction theory was less helpful than it could be with further development. In what follows, I sketch a few of the issues that are not adequately addressed in existing auction theory.

5.1 Aggregation of Multiple Licenses

One of the main strategic questions that the bidders faced was how best to acquire multiple licenses. The intuition is clear from basic economics. The more licenses that the bidder demands, the higher the price the bidder pays on all the licenses of that type. Hence, there is a cost associated with demanding an additional license. The cost is equal to the increase in price times the number demanded less one. The increase in price depends on the industry demand curve, which is uncertain to the bidders.

Deciding when to reduce demand or move down to less desirable licenses is an important and complex question. A good example of this came in round 11, when PageNet decided to move from three 50/50s to two 50/50s and a 50/12.5. By continuing to demand three 50/50s, PageNet would probably cause prices to rise on the 50/50s to a point where PageNet would want just two 50/50s. The additional inbound capacity from three 50/50s was not needed in their VoiceNow service, so PageNet assigned a much lower value to the last 37.5 kHz of inbound capacity. Hence, it made sense to move off one of the 50/50s. In making this decision, it is essential for the firm to *anticipate* where prices are likely to go as a function of its demand. The strategic gain is lost if the firm simply reacts to current prices. Keeping a close eye on bidder activity and recognizing the possibility of "signal jamming" behavior are critical to assessing where prices are likely to go. When there is great excess demand, it is safe to predict that prices will go much higher.

It is the aggregation of multiple licenses that makes auction design so complex. The basic results from auction theory simply no longer apply. For example, in a multiple-object auction, it is no longer the case that an ascending-bid auction is efficient. Inefficiencies can occur if the bidder with the highest value for a particular combination of licenses does not bid for the aggregation gains, because it views the prospect of winning the combination unlikely. The high-valuing bidder rationally decides to stop bidding for the combination, since continuing in the bidding exposes the bidder to too much risk that it will be stuck with the "dogs"—licenses that are only valuable in combination with others.

An obvious answer to this aggregation problem is to allow combination bids, but this introduces other potential inefficiencies. With combination bids, a firm bidding for a large combination of licenses may win the combination when others value the individual licenses more. The individual bidders are unable to topple the combination bidder, because of a free-rider problem. Each individual sees that it is hopeless to outbid the combination bidder by its *individual* action. What is needed is for all the individual bidders to raise the bidding on the individual licenses, but each bidder has an incentive to let the others do the raising. Combination bids not only increase complexity, they introduce potentially serious inefficiencies.

An alternative is to dispense with the ascending-bid design and instead use an efficient dominant strategy mechanism, à la Vickrey (1961). Although designing such a mechanism may be straightforward theoretically, it would pose insurmountable implementation problems for the FCC. Chief among these are issues of commitment and complexity. From a political perspective, it is essential that the bidding process be public. Hence, it would be necessary to reveal all the bids, once the auction is closed. But revelation destroys the dominant strategy feature of a Vickrey auction. Even if the auctioneer does not use the winning firm's bid in determining the price, there is no guarantee that other parties will not use this information about the bidder's reservation price in subsequent transactions (Rothkopf et al. 1990). Moreover, the FCC would be ridiculed unjustly in the press for selling the licenses for less than what the bidders were willing to pay.

An important distinction to consider in auction design is the extent to which the licenses are substitutes (submodular valuations) or complements (supermodular valuations). If the licenses are substitutes, then firms' demand curves do not have large jumps and the ascending-bid auction is likely to lead to an efficient outcome. This appeared to be the case in the nationwide narrowband auction, but it may not be the case in the broadband auctions, where aggregation gains may be large. If the licenses are complements, then the demand curves have large jumps and convergence to an efficient outcome with the ascending-bid design may be problematic. More research is needed to determine the magnitude of the problem and the best way of dealing with it. Kelso and Crawford (1982) demonstrate the possible nonexistence of an equilibrium with complements in a closely related matching model. Roth and Sotomayor (1990) discuss the connection

between matching models and auctions with multiple objects. Although there has been some theoretical work on auctions with multiple objects (see Demange et al. (1986), Engelbrecht-Wiggans (1988), Hausch (1986), Maskin and Riley (1989), and McCabe et al. (1990)), none of these issues is addressed fully.

5.2 Wait Till Later

A second strategic decision facing every bidder is whether to wait for subsequent auctions. As is seen in Table III, only 40% of the narrowband PCS spectrum was for sale in this first auction. Would a firm be better off waiting until these later auctions to acquire needed spectrum? The answer, of course, depends on what the bidder expects prices to be in these later auctions. Empirical evidence suggests that a risk-neutral firm may be better off waiting. In both wine auctions and timber auctions, researchers have observed what is known as the "declining price anomaly"—prices of identical items sold in later auctions sell at lower prices (Ashenfelter 1989). One explanation is risk aversion (McAfee and Vincent 1993). A risk-averse bidder would prefer the sure gains from winning today, rather than the uncertain prospect of winning tomorrow. Hence, the bidder is willing to bid higher than the expected sale price in the later auction. Faced with the prospect to buy at favorable terms today, it is difficult for the bidder to wait for a similar but risky opportunity tomorrow. Black and de Meza (1993) offer an alternative explanation for declining prices in auctions in which the seller gives the initial buyer the option of buying additional units at the initial price. If bidders demand multiple objects, then this option will have value and prices should decline. Gale and Hausch (1994) show that declining prices also rise when the winner has the right to choose among the objects that have yet to be sold. If the goods are not identical, declining prices are an implication of the right-to-choose option.

There are other reasons, apart from risk aversion and buyer options, that a bidder would be willing to pay more in the first auction. First, there is a tremendous advantage to having the uncertainty about a firm's spectrum capacity resolved early. This capacity is the basis for marketing and development efforts for PCS services. The sooner the uncertainty is resolved, the sooner the goundwork for PCS services can be set in motion, and the sooner the firm can get to market. Being first to market in an industry with substantial network externalities and significant switching costs has enormous value. Second, the items sold in the later auctions are not identical, since the later licenses are not sold on a nationwide basis. A firm with a nationwide strategy would pay a premium to avoid the aggregation difficulties present in the later auctions.

Alternatively, it is possible that prices will be higher in the later auctions. If there are many firms with regional interests, rather than nationwide interests, prices in the regional and later auctions might be higher than in the nationwide auction. Another reason that prices might rise is that bidders may bid less aggressively in the first auction to make others think that the common value is less. However, this is not successful in equilibrium because it is anticipated by rivals (Hausch 1988).

5.3 Bidding with Budget Constraints

With perfect capital markets, bidders would simply maximize the value of the various license combinations less the cost of the licenses. Unfortunately, for investments of this size, even with large firms, capital markets are not perfect. Raising capital is both time consuming and costly. Bidders must estimate how much capital they are likely to need, and raise these funds before the auction begins. Although it may be possible to raise some money during the auction, relying on such last-minute efforts is risky.[25] Hence, it is realistic to assume that all firms in this and subsequent PCS auctions face budget constraints. A bidder's objective becomes to maximize profit subject to budget constraints. In practice, the budget constraints are more complex than a single bound. They often are best represented by a step function: with a total cost of up to x_1, the cost of the capital is y_1, for total cost between x_2 and x_1, the cost of capital is y_2, and so on. It is likely that many bidders dropped out or reduced their demand because of binding budget constraints rather than low values.

In auctions for multiple items, budget constraints raise a new strategic issue. A bidder now cares how much its rivals pay for licenses. The bidder prefers that a rival pay a high price, so that the rival will have less money available for the purchase and development of other licenses. Because of this effect, it is possible to construct equilibria where the government raises *more* money when the bidders face budget constraints than when capital markets are perfect. This happens when firms engage in "predatory bidding"—bidding above one's value in an effort to raise rivals' costs. On the negative side, predatory bidding introduces another source of inefficiency. Auctions with budget constraints have been studied by Pitchik (1994), Pitchik and Schotter (1988), Che and Gale (1994a,b), and Rothkopf (1977).

25. Mtel was successful in securing additional funds from Bill Gates and Microsoft during the auction; other firms were not successful and were forced to drop out.

5.4 Jump Bidding

Jump bidding was pervasive throughout the auction. 59% of all new high bids were jump bids that exceeded the minimum bid by more than one bid increment. 23% of these jump bids were raises of one's own high bid. This behavior seems to fly in the face of common bidding wisdom and perhaps even common sense.[26] However, there are good reasons for jump bidding, especially in an auction where the aggregation of licenses plays a role. The basic idea is that the jump bid conveys information about a bidder's valuations. It is a message of strength, conveying that the bidder has a high value for the particular license. Moreover, it conveys this message in a credible way. Jump bidding has a cost—it exposes the bidder to the possibility of leaving money on the table. It is precisely this cost that makes the communication credible. A bidder with a low value would not find it in its interest to make a large jump. The gain, increasing the chance of winning the license, would not exceed the cost, the risk of overbidding. It is not enough for the bidder to simply announce, "I have a high value. You had better look elsewhere." All bidders, high value and low value alike, have an interest in making such a statement. To make the statement credible, the words must be backed up by an action that a low value bidder would find too costly.

Figure 5 displays the bid increments by round, stated as a percent of the previous high bid. Although the FCC specified a minimum bid increment of 5% or less throughout the auction, bids far exceeding this 5% minimum were common. The figure also shows bid activity by round, defined as the number of new bids in the round. Interestingly, the size of the largest jump bids follows bid activity closely. Intuitively, this is consistent with the tradeoffs involved in jump bidding. The benefit from signaling a high value is weighed against the cost of overbidding. When bidding activity is high, the cost of overbidding is negligible *unless* a substantial jump is made. Hence, assuming that the benefit from signaling a high value remains roughly constant, the size of the jumps should decline with bidder activity.

Equilibrium jump bidding (or preemptive bidding) has been studied in the context of corporate take-overs by Fishman (1988) and in English auctions by Avery (1994). In related work, Bikhchandani (1988) explores the role of reputations in repeated second price auctions. Rothkopf and Harstad (1994) show that jump bidding can arise, irrespective of signaling, when minimum bid increments are used.

26. One memorable moment in PageNet's first mock auction was when one bidder raised her own bid. Shocked by such behavior, another participant blurted out, "*Why would anyone raise their own bid?*" This became the rallying cry whenever PageNet considered such behavior in the real auction.

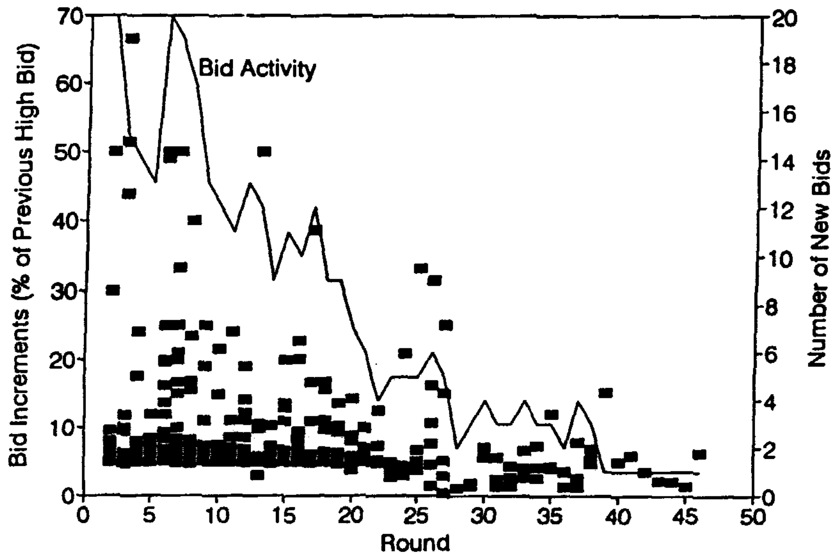

FIGURE 5. BID INCREMENTS AND ACTIVITY (excluding one bid of 138% in round 3).

The minimum increment introduces a discontinuity in the bidding functions, which prompts strategic jump bidding. Jump bidding also arises when there is a cost of bid submission (Daniel and Hirshleifer 1993).

One feature not captured in these models that is important in the PCS auctions is the fact that there are substantial aggregation gains. A desirable collection of licenses is worth more than the sum of the values of the individual licenses. This provides a strong incentive for jump bidding. The value of a license depends on the probability that it and related licenses can be acquired. For example, suppose that there are just two licenses, A and B. Consider a firm that values the AB combination at 20% more than their individual values of $10 each. Clearly the firm should be willing to bid up to $10 each for A and B, but should it bid higher? It all depends on how confident the bidder is about the prospect of forming the aggregation. If another bidder has just made a jump bid from $5 to $10 on license A, the firm should be pessimistic about its chances of forming the aggregation and it should focus on B alone.

In bidding with aggregation gains, the bidders are effectively engaged in a war of attrition. (See Krishna and Morgan (1994) for an analysis of the war of attrition and its relation to auctions.) One way to think of jump biding is that a jump bid effectively "selects" the asymmetric equilibrium favoring the jump bidder in this war of attrition. At first glance, many may view jump bidding as introducing inefficiencies not present in a "Japanese"-style auction. However, jump bidding actually may be a more efficient means of signaling a high value than the screening in the symmetric equilibrium.

5.5 Asymmetric Bidders

Nearly all of auction theory focuses on the case of bidders that are symmetric ex ante.[27] This allows the researcher to focus on symmetric equilibrium bidding strategies, which greatly simplifies the analysis. This focus on symmetric bidders limits the application of auction theory and can be misleading. In most practical situations, there are significant differences in the bidders ex ante. The nationwide narrowband auction is a good example. Of the 25 bidders, a few bidders were known to have high values because of their large market share, prior product development, or other advantages. PageNet, for example, had by far the largest market share in paging going into the auction. It also had a well developed product, VoiceNow, that required a substantial slice of narrowband spectrum for nationwide distribution. McCaw was known to have deep pockets, as were some of the other large firms (AirTouch and BellSouth). These differences were known by all. The relevant auction model to analyze was clearly one with asymmetric bidders. However, such models have yet to be developed in any detail.

One area where an asymmetric bidding model would be helpful is in determining the appropriate bidding discount. Intuitively, it is clear that the optimal bidding discount will depend on any ex ante asymmetries, but without more theoretical work it is difficult to say more.

5.6 Joint Bidding and Collusion

A political issue that has been troubling the FCC throughout the auction design process is how to encourage broad participation in the spectrum auctions. Congress had mandated that the FCC design the auction to encourage participation in PCS auctions by women, minorities, and small businesses. This represents a significant challenge given that the offering of PCS services requires extensive technical knowledge and has large economies of scale. In short, it is difficult for parties outside of the telecommunications industry to participate in an efficient way. Recognizing these problems the FCC has devel-

27. Exceptions are Myerson (1981), Maskin and Riley (1983), and Marshall et al. (1994).

oped a menu of rules that favor women, minorities, and small businesses on a subset of the licenses. Paradoxically, favoring these groups may increase government revenues. By favoring a disadvantaged group of bidders, these bidders become more effective competitors with the large telecommunication incumbents. This leveling of the playing field stimulates competition and raises seller revenues (Myerson 1981).

To encourage small firms to participate, the FCC allows the formation of bidding alliances for joint bidding. By banding together small firms may be able to reap economies of scale that would not be available to them if they bid alone. In future auctions, the FCC allows bidders to form an alliance during the bidding, so long as the firms have applied for disjoint sets of licenses. Debrock and Smith (1983) show that allowing joint bidding in a common value auction does not necessarily lead to lower revenues. Although the number of bidders is reduced, so too is the winner's curse, which allows the bidders to bid more aggressively. Indeed, in the PCS auctions, joint bidding is apt to increase revenues, since it helps the smaller bidders become more effective competitors to the incumbent firms.

Joint bidding could be a problem if it became so extensive that there would be only a few bidders for each license. However, given the large number of firms involved and the enormous gains from deviating from such a collusive posture, it is almost inconceivable that collusion could persist in such a public process. Collusion has been a problem in some auctions in the past;[28] however, it should not be difficult for the FCC to discourage collusion among large public firms.

One of the rules in the initial auction intended in part to limit collusion was keeping bidder identities secret. Based on the nationwide auction experience, the FCC has since decided to reveal bidder identities in subsequent auctions. It was felt that the bidders were able to figure out who was who, despite the confidential bidder numbers, so that little was gained by the attempt at secrecy. This change will enable firms to focus more on bidding strategy and less on public surveillance. It should have no effect on collusion, since under the old rules colluding firms could exchange bidder numbers. Really the only advantage of concealing identifies is that it might reduce predatory bidding. However, predatory bidding is most likely in situations where there are large ex ante asymmetries among the firms, but this is the case where firms are most able to uncover identifies, regardless of the FCC's efforts to conceal them. On balance, the benefits of revealing identities would seem to outweigh the costs.

28. See Baldwin et al. (1994), Feinstein et al. (1985), Graham and Marshall (1987), Hendricks and Porter (1992), McAfee and McMillan (1992), Moody and Kruvant (1988), and Porter and Zona (1993).

5.7 Controlling the Pace of the Auction

A main concern of bidders in the nationwide auction was whether the auction would come to a natural end, according to the simultaneous stopping rule. Many bidders feared that the FCC would be forced to declare a final round of bidding if the FCC did not take steps to control the pace of the auction. This fear was based on the fact that the FCC originally only budgeted enough time to allow at most 26 rounds. Bidders believed that the FCC had grossly underestimated the number of rounds needed to reach closure in a simultaneous multiple-round auction. This fear was confirmed by the auction simulations, which suggested that the time to closure was more apt to occur after between 40 and 80 rounds, depending on the auction rules and bidder values.

Bidders and the FCC wished to avoid a declared final round because of the inefficiencies it would introduce. Much of the benefits of the simultaneous multiple-round auction is lost if a final round of bidding is declared. There are two main problems. First, equivalent licenses may go for substantially different prices. If several bidders with high values happen to bid on the same license, that license will sell for a premium, while other equivalent licenses may go for substantially less if only bidders with low values happened to bid on them. Second, a bidder's values will typically depend on the combination of licenses it is able to obtain. In a final round, a bidder is unable to express its valuations for license combinations in an effective way. See Engelbrecht-Wiggans and Weber (1979) and Lang and Rosenthal (1991). For example, the second 50/50 kHz license may be worth substantially less than the first to a bidder. Should the bidder bid high on one 50/50 kHz license and bid low on a second? Such a strategy is risky—the bidder may lose on both if it happens that another bidder happened to place its high and low bids on the same licenses. The alternative of bidding high on both (in the hopes of winning one) is equally risky. The bidder may win two at high prices, even though only the first 50/50 kHz license is highly valued. Exposing the bidders to these strategic risks creates inefficiencies, discourages bidding, and reduces auction revenues. Faced with these potential inefficiencies, it is not surprising that there was an industry consensus against declaring a final round of bidding.

In assessing how long the auction may last, it is important to make conservative assumptions about bidding behavior and bidder values. Only in this way can the FCC be confident that the auction will conclude in the available time. A conservative bidding strategy is for a bidder to look at the current high bids and to bid the minimum bid on the licenses that represent the best value, given the bidder's preferences. Bidding at or near the minimum bid avoids the risk of leaving money on the table. Given the great uncertainty about when bidders are likely to drop out, this is a prudent strategy.

This assumption is insufficient to predict the number of rounds needed to reach closure. There remain two large uncertainties. First, no one knows what the market-clearing price of the licenses will be. The higher these prices, the longer it will take to reach closure. Second, it is difficult to predict how quickly prices will rise, since it is likely that bidding activity will shift to different groups of licenses from round to round. It is likely that a license will increase in price in only a minority of the rounds. Toward the end of the auction it is especially likely that the pace will slow as bidders drop out.

Industry Recommendations

In order to avoid a declared final round of bidding, the industry recommended that the FCC modify the auction procedures as follows:[29]

- **Adopt contingencies for extending the auction.** Given the large uncertainties about bidder values, bidder behavior, and auction implementation, the FCC should have viable contingency plans for extending the auction beyond Friday, July 29. Even if it is unlikely an extension will be necessary, it would be unfortunate if a final round was forced in this first auction, because of a lack of viable options.
- **Increase the minimum bid increment in the early rounds.** Increasing the minimum bid increment in the early rounds can make a substantial difference in the time to reach closure. Moreover, this is the most desirable way to increase the pace of the auction. It increases the pace precisely when it is most valuable and the cost of doing so is smallest.
- **Extend the hours of the auction.** The FCC's proposal allowed for only about 30 rounds. By extending the hours, about 60 rounds could be conducted over the five days.
- **Reduce the duration of a round.** The FCC proposed one hour between rounds. This could be shortened to 45 minutes or less. This change is self-correcting. If logistical problems prevent the auctioneer from processing all bids within the shorter time frame, the round would simply be extended.
- **Close a round after all bids are in.** Since the auctioneer knows who the eligible bidders are in any round, the auctioneer can close the round and immediately post the high bids as soon as every eligible bidder has bid.

29. These comments were filed with the FCC on 14 June 1994 by the industry's two trade associations, National Association of Business and Educational Radio (NABER) and Personal Communications Industry Association (PCIA). Most of these recommendations were adopted by the FCC before the auction began.

Adjusting the Bid Increment in Response to Bidding Activity

A critical element of the simultaneous multiple-round auction is the minimum bid increment. With proper adjustment of the bid increment, the auction will come to a timely closure and yet allow bidders to express small differences in valuations. Without proper adjustment, the auction will not close in a reasonable amount of time or it will share the undesirable properties of a single sealed bid auction. In what follows, I present a method for adjusting the bid increment in the nationwide narrowband PCS auction. The method was designed and tested using the simulation described earlier.

The simultaneous multiple-round auction is most similar to an English auction. In an English auction, the auctioneer plays a key role in adjusting the bid increment throughout the auction. With a simultaneous multiple-round auction, adjustment of the bid increment is even more important for two reasons. First, there is a significant amount of time between rounds (say, an hour) rather than a few seconds as in an English auction. Adopting a pace that is too slow would add days to the auction, rather than minutes. Second, because there are many items for sale in the simultaneous multiple-round auction, many more rounds are needed to reach closure than in an English auction for a single item. As bid activity falls, it becomes more likely that it will take several rounds for the price of a particular type of license to increase by a single bid increment.

The importance of the bid increment stems from the fact that bidders may bid near the minimum bids in any round. As in an English auction, aside from signaling issues, there is little reason to raise a bid by more than the bid increment. Doing so exposes the bidder to the risk of leaving money on the table. A bidder knows that if its bid is not the highest in this round, it will have an opportunity to bid again in subsequent rounds.

Of course, a bidder could bid well above the minimum bids in an effort to hasten the auction. But this individual action is unlikely to be effective. Other bidders will simply shift to the other licenses and continue with the minimum increments. The bidder could place a high bid on all licenses, thereby forcing a rapid pace. But this strategy involves enormous risk (the possibility of substantial withdrawal penalties) for little gain (a more timely closure and a reduced risk of a declared final round). Moreover, there is a free-rider problem. Every bidder has the incentive to let the other bidders take the risk of overbidding. Timely closure is unlikely to be assured by the aggressive behavior of an individual bidder.

Principles of Bid Increment Adjustment

There are five basic principles for an effective method of adjusting the bid increment:

1. *Start large.* It is best to have a large bid increment early, when there are many bidders. A large increment quickly brings the price level to a point where bidders start to drop out. In the early rounds, bidding activity is great and there is no cost to a large increment. The large increment simply saves valuable rounds—rounds that are better used at the end of the auction.
2. *End small.* Toward the end of the auction, the bid increment should be small, allowing the bidders to express small differences in valuations. A small increment increases efficiency and government revenues. It reduces the importance of gaming and strategy.
3. *Reduce the increment as bidding activity falls.* As bidding activity drops the bid increment should fall. The best way to measure bidding activity is the number of new bids in the prior round across all licenses. This is a better measure than the number of new *high* bids, since it is possible for there to be great activity with all the activity concentrated on a single license. This would happen if a particular license was relatively underpriced. Since the licenses are substitutes, it is important to use the same bid increment (adjusting for the size of the license) across all licenses. Waivers should not be counted as new bids, since a waiver does not indicate a willingness to raise prices. Indeed, waivers may be used by bidders who are unwilling to bid under the current bid increment, but who are hopeful that the increment will fall in subsequent rounds.
4. *Avoid large drops in the bid increment.* The bid increment should decline gradually with bidding activity. Large drops (say, dropping from 10% to 5% when activity falls below a particular level) introduce more complex strategies. For example, bidders may use waivers strategically, anticipating a large drop in the increment. Faced with a large drop in the increment, bidders are more apt to regret a prior bid.
5. *Adopt and announce a plan for bid increment adjustment.* The FCC should adopt and announce a plan for adjusting the bid increment before the auction begins. By adopting a sensible plan up front, the FCC can focus on other things during the auction. Some modifications may be needed as the auction proceeds, but these changes would be minor relative to the changes needed under the current plan. With the current plan, the FCC's behavior is more apt to be viewed as arbitrary. The prior announcement of the plan allows the bidders to develop bidding strategies in light of specific rules.

Bidding is more apt to be orderly and rational. As a result, efficiency improves.

A Simple Method for Bid Increment Adjustment

The following method for adjusting the bid increment is consistent with the principles above. The increment in any round depends on the number of new bids in the prior round. If there are more than 25 new bids in the prior round, the bid increment is the greater of $.10 per MHz-pop or 25% of the prior high bid. If there are fewer than 5 new bids in the prior round, the bid increment is the greater of $.02 per MHz-pop or 5% of the prior high bid. As the number of new bids falls from 25 to 5, the bid increment falls linearly from 25% to 5% ($.10 to $.02 per MHz-pop), dropping 1% ($.004 per MHz-pop) with each fewer bid made.

This bid increment approach accomplishes the five goals above. The bid increment is large initially and declines gradually as bid activity lessens. It is simple and responsive. If bidding activity is slight in the initial round, the increment immediately drops to an appropriate level in the next round. For example, if no firms are willing to bid the minimum bids in the initial round (every firm submitted a waiver), then the bid increment and the minimum bid drop to $.02 per MHz-pop.

To evaluate this method, I conducted 777 auction simulations. The simulation parameters are given in Table VI. Figure 6 shows the

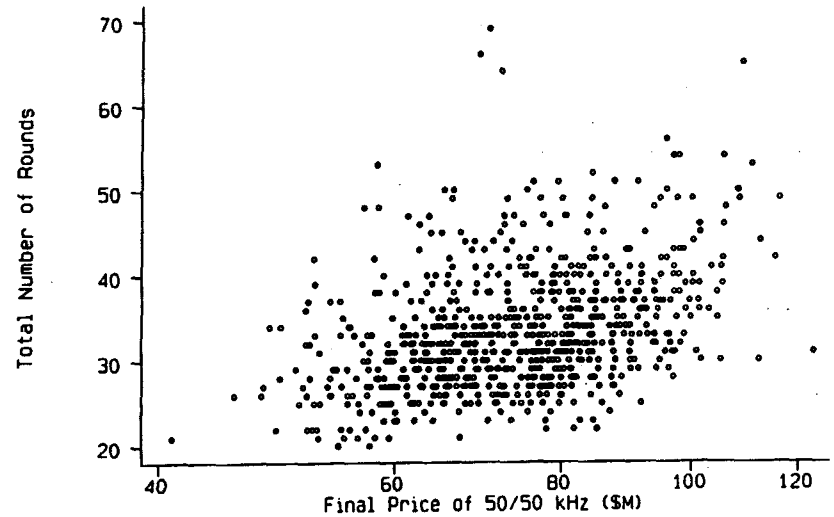

FIGURE 6. NUMBER OF ROUNDS; INCREMENT FROM 25% TO 5%: Based on 777 auction simulations; bid increment falls from 25% to 5% as new bids fall from 25 to 5.

number of rounds to close as a function of the final sale price of a 50/50 kHz license. Several conclusions can be drawn from the simulations:

- The number of rounds is not too sensitive to the final prices. About eight additional rounds are needed with each doubling of prices.
- The total number of rounds is likely to be under 60 rounds even if the final prices are high. In only 4 cases out of 777 (0.5%) were more than 60 rounds needed.

A further advantage of this method is that the FCC can make minor adjustments to the plan in response to unforeseen difficulties. Although adjustments are unlikely to be necessary, the FCC may find that after 40 rounds bidding activity is still high. In this case, the FCC can announce that the bid increment will not fall below 8%; that is, it will reach its minimum when the number of new bids in the prior round has fallen to 8, rather than 5. Likewise, the FCC might find that bidding activity is slight after only 15 rounds. In this case, the FCC can announce that the bid increment will continue to fall to 3% when there are three new bids in the prior round. In this way, bidders will be able to express smaller differences in value, if there is sufficient time.

This method depends on just two parameters: an activity level upper bound (25), that defines the maximum bid increment, and an activity level lower bound (5), that defines the minimum bid increment. For all activity levels between these upper and lower bounds, the percentage bid increment is n and the absolute increment is $\$.004 \cdot n$, where n is the number of new bids in the prior round. I have chosen the upper and lower bounds so that it is extremely likely that closure is reached within 60 rounds.

This method can be extended to auctions for regional, MTA, or BTA licenses. In doing so, there are two issues that need attention. First, different licenses may have substantially different values in terms of MHz-pops because of different population densities, or some other factor. Hence, it does not make sense to start the bidding on all licenses at the same level per MHz-pop. The solution is not to have a minimum bid until after the license has been bid on. Second, the best measure of bidding activity needs to be determined. One reasonable measure would be counting the number of bids in terms of MHz-pops relative to the total MHz-pops being auctioned. Such a method would work regardless of the size of the licenses, either geographically or in bandwidth. The parameters for setting the bid increment and for determining the transition between auction stages should be set using a detailed simulation of the particular auction.

There was a consensus among auction experts that tying the bid increment to bid activity was a good idea. Moreover, the consensus view was that this particular procedure would result in a pace that was about right. The FCC concurred, but decided not to announce a particular bid increment procedure, since actual bidding behavior was still uncertain and the FCC wanted to maintain maximum flexibility to respond to the unforeseen. It was at this point, two weeks before the auction, that the FCC decided to use a panel of auction experts to control the pace of the auction.

Activity Rules

A second instrument for controlling the pace of the auction is the activity rule. A properly designed activity rule will encourage sincere bidding without limiting a bidder's strategic options in an important way. In the nationwide narrowband auction, the activity rule is simple. In stage 1, a bidder must be active on at least one license in every round; in stage 2, a bidder's eligibility is reduced to the number of licenses the bidder is active on in the prior round. A bidder is active on a license if it places a valid bid on the license or it was the high bidder in the prior round. Hence, in stage 2, a bidder desiring three licenses at the current prices must be active on three licenses. As it turned out, the FCC was so pleased with the way that things were going throughout the nationwide narrowband auction that it never moved to stage 2. Said one FCC staffer, "Why mess with the rules when things are going so well?" By Wednesday, the FCC became convinced that no one was "hiding in the grass" and that stage 2 was unnecessary.

Had the FCC declared a stage 2 some time on Wednesday or later, it would have had little effect on the outcome. Declaring stage 2 would have prevented the insincere bid of $71 million each on licenses 2 and 3 by PageMart in round 29. However, PageMart would have been able to accomplish the same thing by bidding $71 million in two consecutive rounds. Declaring stage 2 would also have prevented Mtel's insincere bids on only a single 50/12.5 license in rounds 20 and 21.[30]

In the broadband auctions and the subsequent narrowband auctions, the activity rules will play a much more important role. There are two reasons for this prediction: (1) there will be a much larger and more diverse set of licenses, and (2) aggregation issues will be much more complex and important. In these auctions, the FCC has decided to use the Milgrom–Wilson activity rule. There are three stages, which require increasing levels of activity to maintain eligibility. In stage 1,

30. In these rounds, Mtel might have been waiting for a commitment from William Gates and Microsoft for more funds.

a bidder's maximum eligibility is three times its activity in the prior round. In stage 2, maximum eligibility is 1.5 times its activity in the prior round. In stage 3, maximum eligibility is 1 times its activity in the prior round. Activity is measured as the number of MHz-pops on which the bidder placed a new bid or was the high bidder from the prior round.

This activity rule does a good job of encouraging sincere bidding, especially in stage 2 and stage 3. However, I am concerned that stage 3 is too harsh. It limits flexibility too much. This is especially a problem with large licenses (regional or MTA auctions). For example, suppose a firm's first choice is the Miami MTA (population 5.4 million) and its second choice is Tampa (population 5.7 million). In stage 3, the firm is prevented from switching from Miami to Tampa, should Tampa become a better value. Once stage 3 is declared, the bidder for Miami is forced to bid on Tampa to keep both options open. Such strategic bidding can lead to inefficiencies.

The FCC recognized this problem in the regional narrowband auction and modified stage 3. In stage 3, a bidder must be active on 90% of its eligibility; otherwise, eligibility is reduced to 1/.9 of its prior activity. This 90% rule probably strikes a better balance between encouraging sincere bidding and maintaining bidder flexibility. A further enhancement would reduce the large discontinuities created by a three-stage activity rule. Instead, the activity requirement could move continuously with a measure of bid activity (measured either as the number of megahertz-pops of activity or the percentage increase in total spending). Much work remains to be done in analyzing the ramifications of various activity rules. However, one thing seems clear. Activity rules should be used *in conjunction with* bid increment rules that tie the bid increment to bidding activity. In some sense, the activity rule is a more draconian instrument than the bid increment rule, and therefore it can lead to greater distortions. In the example above, the activity rule prevents the firm from ever bidding again on Tampa (unless the bidder bids strategically), whereas the bid increment rule is self-correcting. If the bid increments are so high as to choke off the bidding, then in the next round the increments are reduced. However, activity rules are needed to assure a timely closure of the auction—relying on bid increments alone is insufficient.

6. CONCLUSION

The FCC's first spectrum auction was a welcome event for economists. After decades of lobbying for auctions, economists finally got their way and witnessed the wisdom of their recommendations. Nearly every constituent benefits from auctioning the airwaves. Taxpayers, consumers, and firms are all better off with auctions. The only losers are inefficient firms, which are unsuccessful in the auctions, but have a chance in lotteries or comparative hearings.

The success of this first "experiment" with simultaneous multiple-round auctions means that the FCC can move with confidence into the regional narrowband auction (October 1994) and the MTA broadband auction (December 1994). These two auctions will use essentially the same auction rules as in the nationwide auction. The only significant changes are: (1) allowing firms to form alliances during the auction as long as the firms are bidding for disjoint sets of licenses, and (2) revealing bidder identities.

The success of the spectrum auctions should encourage the government to use auctions of this form in other applications, such as airport landing rights (Rassenti et al. 1982), pollution rights (Cason and Plott 1994), mineral rights, and hazardous waste (Kunreuther and Kleindorfer 1986). It is easy to think of other applications, such as the allocation of university resources (Boyes and Happel 1989).

The good news is that auctions for spectrum are here to stay. The auction outcome is compelling to taxpayers. So long as budget deficits remain a problem, it is hard to imagine that Congress would be able to reverse the auction decision without setting off a grassroots rebellion among taxpayers. Indeed, the auction outcome is so compelling that the FCC had to reverse its decision on the Pioneer's Preference awards. On December 24, 1993, following through on a policy adopted before the FCC was granted auction authority, the FCC gave away four premium licenses, worth well over one billion dollars, to firms as a "reward" for the firms' development of "pioneering technology." These awards, intended to inspire research and development in communications, were really nothing more than a holdover from the days of comparative hearings. On August 9, 1994, under pressure from Congress, the FCC announced that the Pioneer winners would be required to pay 90% of the winning bids of similar licenses.[31]

31. The pressure came in the form of legislation introduced by John Dingell that would withhold the FCC's appropriations unless it made the Pioneer winners pay 90% of the auction price. The four Pioneer winners are: Mtel (which won a nationwide 50 kHz unpaired), American Personal Communications (which won a Washington 30 MHz MTA), Omnipoint Corp. (which won a 30 MHz New York MTA), and Cox Enterprises (which won a 30 MHz Los Angeles MTA). The FCC's reversal on August 9 was challenged in court by the Pioneer winners. Since then, Congress introduced legislation tied to GATT (General Agreement on Trade and Tariffs) requiring that the broadband Pioneer winners pay 85% of the average auction price per pop in the top twenty markets, excluding New York, Los Angeles, and Washington. (*Washington Post*, October 5, 1994, p. A1.) This strange pricing rule, which excludes the most relevant markets, was negotiated for political reasons. Since New York, Los Angeles, and Washington will sell for a premium on a per pop basis, this rule enables the Pioneer winners to pay less than 85% of the other license in the relevant market, but have the appearance of getting only a 15% discount.

The sentiment of the auction winners was summed up by Terry L. Scott, President of Paging Network, Inc., "Through these newly acquired narrowband PCS frequencies, wireless messaging companies will offer advanced communications services to businesses and consumers that may fundamentally change when, where, and how people communicate. For a company such as PageNet, the largest wireless messaging company in the country, frequency is our lifeblood and the frequency we acquired provides us the raw material we need for significant future growth." FCC Chairman Reed Hundt also was delighted with the outcome, "We're happy the [federal budget] deficit issue is being addressed so successfully." (*Washington Post*, July 30, 1994, p. A1.) "All budget targets for this fiscal year have been substantially exceeded." (*Wall Street Journal*, August 1, 1994.)

Gone are the days of comparative hearings and lotteries. From consumers and firms can be heard a collective cheer: Good riddance!

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